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S-wave measurements and seismic site classification in the Hispaniola Island

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ABSTRACT: A proper dynamic characterization of soils is essential for an effective seismic site response evaluation. A typical approach consists in the determination of dynamic properties at low strain levels by means of in-situ shear wave velocity measurements. In-hole (e.g. Cross-hole and Down-Hole) and surface (e.g. SASW and MASW) methods are the most common techniques used worldwide. For the evaluation of seismic site effects in "regular" subsoil conditions, a simplified approach is based on a soil classification, according to an average shear wave velocities (e.g. $V_{S,30}$). Here two case-histories of geotechnical characterization of two different areas in Hispaniola Island are illustrated, where proper dynamic in-situ tests allowed to individuate complex subsoil conditions. Then, according to national codes, subsoil categories and related seismic site responses are evaluated: the shortcomings of such code approaches are highlighted, and suggestions for more effective seismic action evaluation are suggested.

1 INTRODUCTION

This paper deals with the geotechnical characterization of subsoils finalized to the evaluation of the site seismic response, according to the current national codes of Hispaniola Island: Reglamento para el Análisis y Diseño Sísmico de Estructuras, R-001, Decreto 201-2011, Rep. Dominicana (MOPC, 2011) and Code National du Bâtiment d'Haïti (MTPTC, 2012). At this aim in paragraph 2 a general overview of the seismic hazard of the island is illustrated, and the seismic soil classification based on the average shear wave velocity ($v_{S,30}$) is discussed. In particular, the soil classification proposed in the Hispaniola Island codes is compared with those suggested by Eurocode 8 (EC8, 2004) and the Italian code (Norme Tecniche per le Costruzioni, NTC2018); the latter takes into account the results of more recent research advances.

Hence in the following paragraphs two case-histories of geotechnical investigations and seismic action evaluation performed in two different sites are presented. The first study was performed at Punta Catalina power plant site, in the South-West of Dominican Republic, for determining the actions on the industrial buildings. The latter was performed at Port-au-Prince, Haiti capital, after the 2010 earthquake, for interpreting the correlation between the soil conditions and the damage distribution. In both sites different investigation techniques were carried out, and the combined analysis of the obtained results allowed the reconstruction of difficult subsoil conditions, which are not unusual for Hispaniola Islands, due to its recent and very complex tectonic history. On the basis of the measured shear wave velocities, and the computed $V_{S,30}$ values, at any point in the investigated area the soil classification and seismic actions are estimated (as defined in the Hispaniola Island codes). The obtained results are critically discussed and compared with those derived by the application of EC8 and NTC2018 criteria. Detailed comments on the comparison between the different code results and final conclusions are then illustrated.

2 HISPANIOLA ISLAND: SEISMIC HAZARD AND REGULATIONS

Hispaniola Island is a high seismicity region, due to the fact that it is located on the Northern edge of the Caribbean plate, at the contact with the North America plate: this produces a pattern of sub-horizontal subduction faults capable of generating large magnitude earthquakes (Figure 1). The two main seismic faults are the Northern one, located in the Atlantic Ocean at the border of the North American plate, and the so-called "Plantain Garden-Enriquillo-Los Muertos fault", located in the Southern part of the island. The latter crosses the island in the Western side (Haiti), passing beneath the area of Port-au-Prince city (Haiti), and Jimaní and Duvergé cities (DR), then develops toward South-East in the Caribbean Sea, hence quite far from the Southern coast of the Dominican Republic until the southern part of Puerto Rico island.

The seismic hazard on outcropping rock is classified in the codes of the two countries, Haiti and Dominican Republic, in terms of expected spectral accelerations for given return periods of the earthquake (T_R). In particular two spectral accelerations are given: Ss for structural period of 0.2 s, and S_1 for structural period of 1.0 s. For example, in Figures 2 and 3 the spectral reference iso-acceleration maps of Ss and S_1 for an earthquake return period of 2,475 years, given in the Dominican Republic and Haiti codes respectively, are plotted.

Local soil effects are taken into account by means of so-called site factors Fa and Fv, which multiply Ss and S_1 spectral accelerations respectively. Fa and Fv values mainly depend on the

Figure 1. Main seismic faults of the Hispaniola Island and major earthquakes since 1562 (Updated 2018).

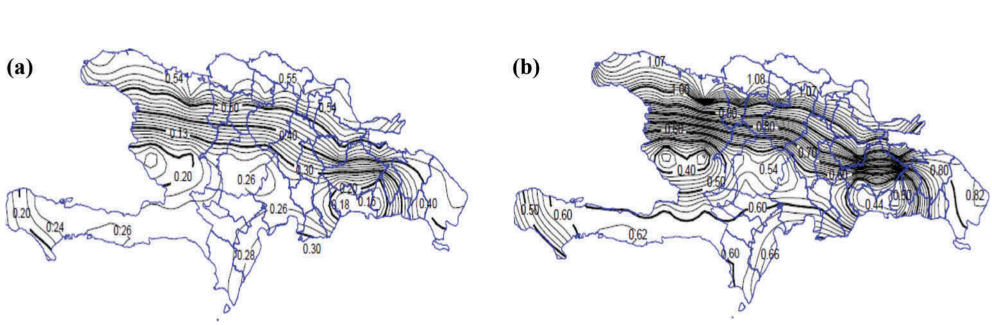

Figure 2. Spectral iso-acceleration (in terms of g) maps of (a) S1 and (b) Ss for a 2% probability of exceedance in 50 years, i.e. TR=2475 yr, according to the Dominican seismic code (MOPC, 2011).

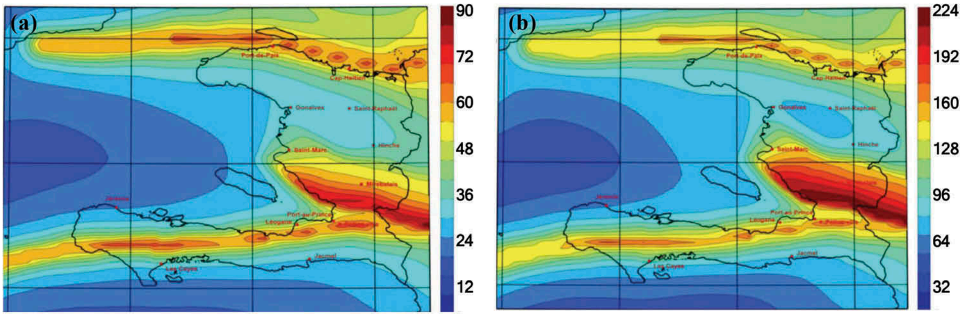

Figure 3. Spectral iso-acceleration (in terms of percent of g) maps of (a) S1 and (b) Ss for a 2% probability of exceedance in 50 years, i.e. T_R=2475 ys. (Haiti National Building Code, CNBH 2012).

"site class" of the subsoil: 6 classes of sites are identified, from A to E, as a function of the soil stiffness of the first 30 m, starting from a reference level (depending on the structure typology).

The soil stiffness can be determined by the values of one of the following three different parameters: the shear wave velocity V_S, the number N of SPT test, the undrained shear resistance Su (see Table 1). If the subsoil is not homogeneous, average values of such parameters have to be computed; for the shear wave velocity see the classical average $V_{S,30}$ formula:

$$V_{s,30} = \frac{30}{\sum_i \frac{h_i}{V_i}} \tag{1}$$

where h_i and v_i denote respectively the thickness and the shear wave velocity of the i-th layer.

This $V_{S,30}$ formulation is the same of Eurocode EC8, but with an important difference in its utilization. In fact, according to Hispaniola Island codes, this average value can be utilized for any kind of subsoil stratification, even if rocky layers are present in the reference 30 meters. On the other hand, EC8 clearly states that it can be applied only for subsoils made of soils, hence

Table 1. Site classification according to the Dominican Seismic Code (MOPC, 2011)

Site Classification	Description	Properties of soils in the 30 meters deep: Shear wave velocity (m/s)	Standard Penetration Test (N)	Undrained Shear Strength Su, (Kg/cm^2)
A	Very Hard Rock	Vs > 1500	N/A	N/A
B	Rock	760<Vs≤1500	N/A	N/A
C	Soft Rock and Very Dense Soil	360<Vs≤ 760	N > 50	Su ≥ 1.0
D	Stiff Soil	180≤ Vs≤ 360	15≤ N ≤ 50	0.5 ≤ Su ≤ 1.0
E	Soft Soil	Vs < 180	N < 15	Su < 0.5
E	Any subsoil with a surface layer with thickness ≥ 3 m, having the following characteristics: • Plasticity Index Pl > 20. • Water content w ≥ 40%. • Undrained Shear Strength S_u < 0.2 Kg/cm^2.			
F	Any soil that has one or more of the following characteristics: • Soils that could suffer liquefaction during strong earthquakes. • "Peats" and/or clays with a large amount of organic material with thickness more than 3 m thick. • Clays with PI > 75 and thickness ≥ 7.5 m • Soft clays with thickness ≥ 35.0 m and Su ≤ 0.5 Kg/cm^2			

N/A: Not Applicable

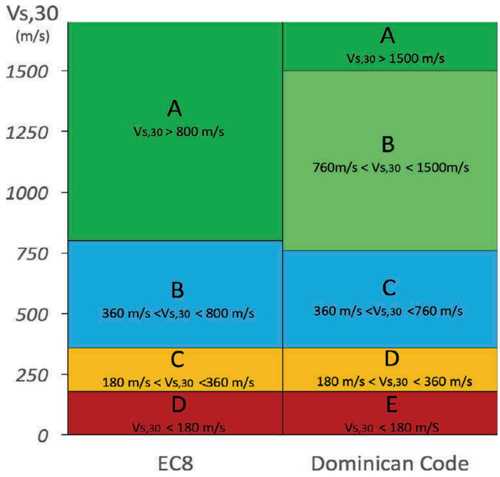

Figure 4. Comparison between site classes (defined exclusively by means of $V_{S,30}$) according to Eurocode 8 (EC8) and Dominican seismic code (MOPC, 2011).

leaving a shadow zone in the application of such approach if there are rocky material in the reference 30 meters (with the particular exception of site class E, which takes into account only the case of alluvial deposits less than 20 m thick, overlying a rock formation). An advance in the application of this criterion is achieved in the recent Italian NTC2018, where the average shear wave velocity is defined as "equivalent" ($V_{S,eq}$), in the sense that it is computed for 30 meters, if no rocky materials are present, while if the so-called bedrock is more surficial, the average velocity is computed down to the bedrock level, for a subsoil thickness lower than 30 m.

Further the Hispaniola Island codes define 2 classes of rocky subsoils: site A ($V_{S,30}$>1500 m/s) and site B (750 m/s<$V_{S,30}$<1500 m/s); on the contrary, EC8 and NTC2018 only indicate one rocky subsoil ($V_{S,30}$>800 m/s). For the rest, the range of values of $V_{S,30}$, for individuating the different site classes, are almost the same, as it is shown in Figure 4, where EC8 and Dominican Republic site classes are schematically compared.

A final important consideration about the different codes' prescriptions regards the use of specific dynamic analysis for evaluating the seismic site response. According to the Hispaniola Island codes, the simplified approach (based on site classification) should be always applied, regardless of soil stiffness distribution with depth; on the other hand, specific dynamic analyses for site response evaluation are even allowed, but the obtained results (in terms of amplification factors) can be utilized only if they are more conservative than those obtained by the simplified approach. On the contrary, both EC8 and NTC2018 clearly state that the simplified approach can only be applied for homogeneous soil and for stratified subsoils characterized by layer stiffness gradually increasing with depth; for any different subsoil condition, specific dynamic analyses should be performed.

3 CASE HISTORY 1: PUNTA CATALINA (DOMINICAN REPUBLIC)

Punta Catalina is a site in the South-West region of Dominican Republic, where a big coal Power Station of 720 MW is under construction (Figure 5a,b). Hence an important and complex geotechnical investigation campaign was planned for the geotechnical characterization of the site. Surface and in-hole surveys (e.g. geophysical tests and boreholes with SPT tests) and specific in-hole and surface shear wave velocity measurement techniques (e.g. Cross Hole and Multichannel Analysis of Surface Waves (MASW) respectively) were carried out (see the map in Figure 5c).

Combining the results of all the surface investigation techniques, which allow to investigate large areas, reliable reconstructions of complex subsoil configurations were obtained (see sections in Figures 6 and 7). These reconstructions would not have been possible by means of only

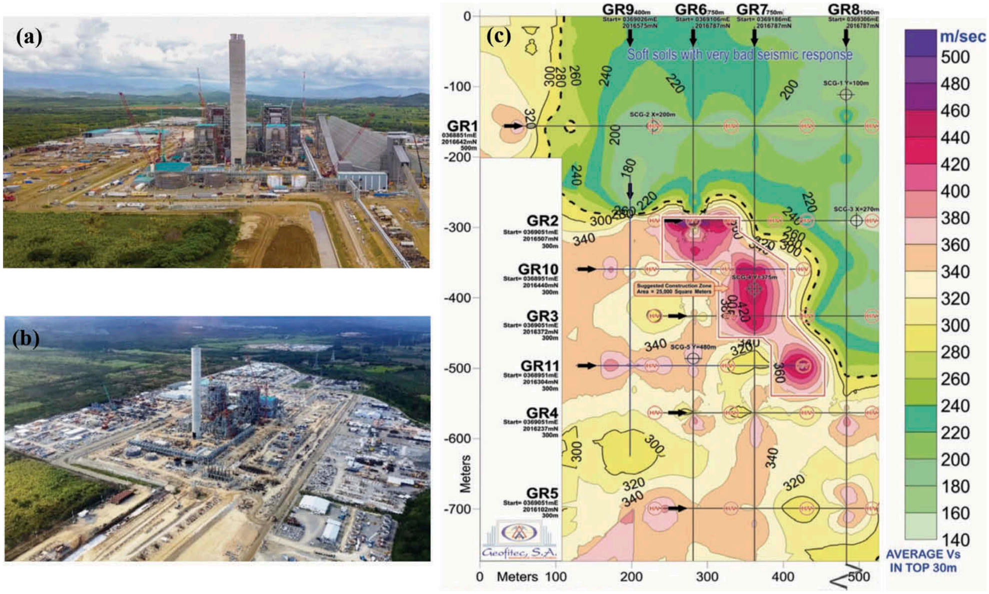

Figure 5. (a,b) Punta Catalina Power Station, and (c) $V_{S,30}$ curves map with location of geotechnical investigations: (MASW lines for shear waves (GR), Cross hole tests (CH), and calibration boreholes (SCG).

in-hole surveys, located quite far from each other. On the other hand, the detailed information achieved by in-hole investigations (both stratigraphic and mechanical properties, such as V_S), allowed to calibrate the soil stratigraphy obtained by surface techniques, and to properly characterize the stiffness (V_S) of each soil bed (see in-hole results in the section of Figure 6).

The final geotechnical interpretation put clearly in evidence that the subsoil conditions are quite variable, both in horizontal and vertical directions, even at a local scale. Generally the subsoil is constituted by calcareous clays, fine sand, gravels, poorly cemented conglomerates, limestone and well-stratified sequences of shale/siltstone/sandstone.

The results of geotechnical investigations were then utilized for the areal seismic characterization, in terms of $V_{S,30}$, in order to determine the design seismic actions according to the Dominican Republic regulations. It is worthwhile noting that a recurrent stratigraphic condition is the presence of rocky materials (V_S>760 m/s) within the first 30 meters from the surface, then affecting the evaluation of $V_{S,30}$ according to the Dominican code.

As an example, referring to the vertical V1 in Figure 7, the so-called bedrock is at a depth of about 18.50 m. Hence, according to the code, a $V_{S,30}$ value quite high is computed (440 m/s,

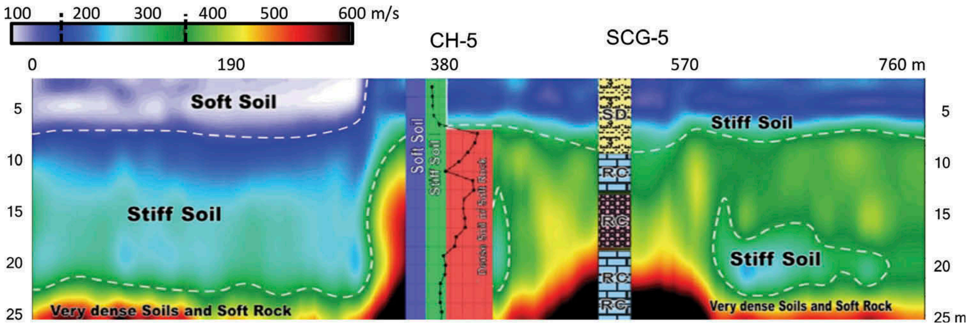

Figure 6. Punta Catalina - Soil section along GR-6 Line.

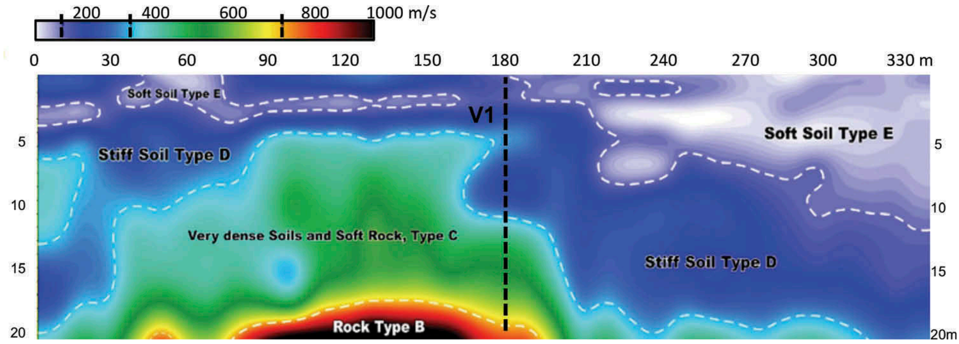

Figure 7. Punta Catalina - Soil section along GR-3 Line.

Table 2. Vertical V1: Dominican Code Site Classes according to VS,,30 and VS, eq

	V_S (m/s)	Site Classification (in parenthesis EC8 and NTC2018 class)		
		DC	EC8	NTC 2018
$V_{S,\,30}$	440	C (B)	NA	-
$V_{S,\,eq}$	339	-	NA	F (E)

DC: Dominican Code; NA: Not Applicable; Site Classification: in parenthesis EC8 and NTC2018 class

because of the presence of 11.50 meters of rocky material) which provides a seismic classification of Site C, equivalent to a stiff subsoil (correspondent to Site B according to EC8 and NTC2018). For this kind of subsoil EC8 classification would not be applicable, because of the presence of rock in the first 30 meters. On the other hand, if we would apply the more recent Italian NTC2018, a $V_{S,eq}$ = 339 m/s would be computed (relative to the first 18.50 m only), providing a more severe subsoil classification as Site F (correspondent to site E of EC8 and NTC2018). The results of such classification comparison are resumed in Table 2.

In conclusion, anytime thick layers of rocky materials are present in the reference 30 m, the seismic site classification according to the Dominican code could be unconservative, hence inducing to underestimate site amplification effects and design seismic actions.

In such cases, provided that the soil stiffness distribution with depth still allows to estimate seismic soil response by means of the simplified approach based on site classes (i.e. stiffness constant or gradually increasing with depth), it would be necessary to adopt a classification based on $V_{S,eq}$, like the one proposed in the Italian NTC2018.

4 CASE HISTORY 2: PORT-AU-PRINCE (HAITI)

On January 12th, 2010 the city of Port-au-Prince, capital of Haiti, located on the West side of the Hispaniola Island, was hit by a strong earthquake of magnitude M=7.0. This earthquake was the most devastating seismic event in Hispaniola Island's history. Extensive damages were located in the Southern and South-Western areas of the city (Figure 8a), where the collapsed buildings were founded on soft clayey soils deposited in an ancient marine channel. In this area, even important and/or recent construction buildings (e.g. the Haitian's Government Palace and the famous Montana Hotel) totally or partially collapsed. On the other hand, minor or no damage was observed on even very poor constructions, located on the Southern slope of the city (Figure 8b), and directly resting on the outcropping Tertiary limestone formation (De León 2012a, b); most of those constructions were probably built without respecting any seismic design regulation.

In order to interpret the correlation between the specific soil conditions and the observed damage distribution, an extensive investigation campaign was planned, mainly consisting of

Figure 8. Port-Au-Prince - 2010 Earthquake: on the left a small village lying over clay was destroyed in the Southern area of the city, and on the right a small village lying over the limestone rock formation remain without any damage.

surface techniques, which allowed both the stratigraphic reconstruction and the evaluation of shear wave velocity of the subsoil over large areas. Here two soil sections investigated across the East side of Port-au-Prince are plotted in Figures 9 and 10, where the shear wave velocities (Vs) measured by the MASW technique are illustrated.

The first soil section (Figure 9) is located close to Port au Prince harbor site. The shear wave velocity pattern is quite uniform along the horizontal direction, and the velocity values generally increase with depth, with the exception of a softer layer between 2 and 4 meters in depth, with V_S of about 75 m/s. It is worthwhile noting that this soft layer, located between two stiffer materials, could have had a significant role on the site seismic amplification during the earthquake;

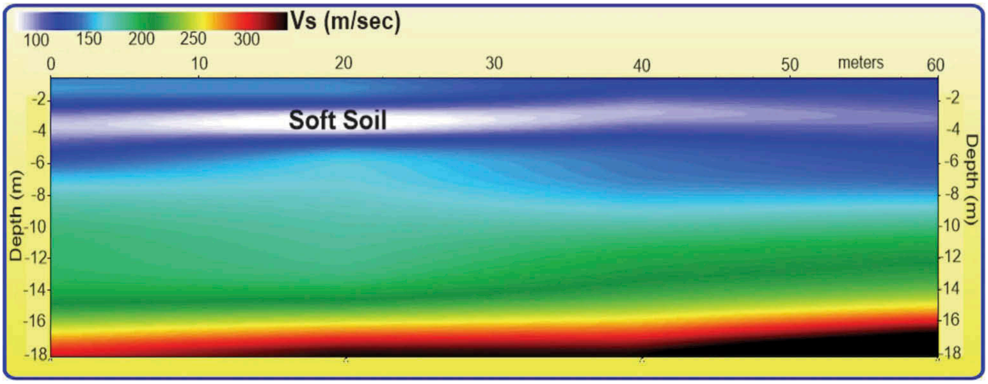

Figure 9. Port-Au-Prince - Soil section by MASW, near Port au Prince harbor site: VS distribution showing a softer soil layer between 2.0 and 4.5 m from the surface.

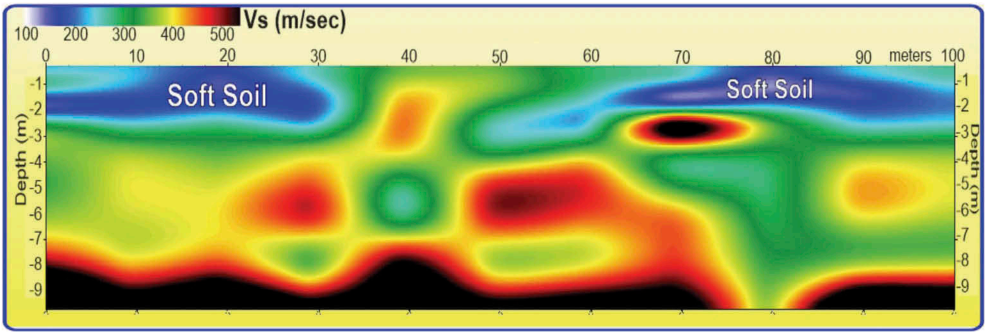

Figure 10. Port-au-Prince - Soil section by MASW, in the area of Haitian Government Palace: VS distribution showing frequent inversions of velocity with depth.

nevertheless this effects should be properly evaluated by specific dynamic analysis. In fact, in this case, the simplified approach based on site classes is inapplicable, both because of the velocity inversion, and because of the presence of rocky materials starting from a depth of about 18 m.

Even more problematic are the subsoil conditions near the Haitian Government's Palace (see the section in Figure 10). Here the V_S pattern is irregular, both in the horizontal and vertical directions. The inversion of shear wave velocity is frequent, and very stiff material are interlayered with softer materials even within the first 10 m from the surface. Once again an evaluation of seismic site effects could be performed only by means specific dynamic analyses, disregarding the indications of the Dominican Code, that always impose the evaluation of seismic action on the basis of the simplified approach (i.e. site classification and related Fa and Fv coefficients).

5 CONCLUSION

In this paper two case-histories of soil characterization for seismic site response in two sites of Hispaniola Island are illustrated and commented. For the geotechnical characterization, both surface and in hole investigations were performed; the combination of the multiple set of results allowed an effective reconstruction of site conditions, both from a stratigraphic and a mechanical point of view, notwithstanding the complex geology of the subsoil. These case-histories confirm that only an effective planning of site investigations based on both surface and in-hole technique can allow to effectively determine the real configuration of complex subsoils.

Further Hispaniola Island seismic hazard is illustrated, and the seismic regulations of the national codes (the Dominican Republic and the Haitian ones) are discussed and compared with the European (EC8) and Italian (NTC2018) ones. In particular the suggested simplified approaches based on site classification and related seismic actions are applied. The following shortcomings of Hispaniola Island codes for complex subsoils are highlighted:

- Hispaniola national codes do not differentiate the use of the average $V_{S,30}$ velocity when the bedrock is quite shallow (as it often happens for typical local subsoils), producing, in such cases, unconservative site classifications and underestimation of amplification effects and design seismic actions;
- if the bedrock is shallower than 30 meters, site response could be evaluated by means of the simplified approach of the NTC2018 code, based on the equivalent $V_{S,eq}$ velocity value;
- anyway, in the case of subsoil characterized by sharp velocity inversion, which is recurrent in the Hispaniola Island because of its recent and complex tectonic history, no simplified approaches can be applied (as indicated by EC8 and NTC2018), and proper dynamic analyses should be performed to evaluate seismic site response.

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